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Enhanced Error-Resilient Video Transport over MIMO Systems using Multiple Descriptions

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Abstract— Much of the work on wireless transmission over the past several years has focused on simulation and deployment of multiple-input-multiple-output (MIMO) systems. These systems provide benefits of improved robustness and enhanced throughput at relatively low cost.

Despite the increased understanding of the performance of MIMO systems, little is known about which combination of channel and source coding yields the best results for video transport. It is clear that new ways of providing error-resilience that emerge from MIMO architectures need to be developed which can cope with the particularities of video content.

This paper proposes a new scheme for video transmission using multiple-description coding (MDC). Two complementary MIMO techniques, space-time block coding (STBC) and spatial multiplexing (SM), are employed. The quality of the reconstructed video, already enhanced by the inherent MIMO systems' properties, is further improved through the use of MDC.

Index Terms—multiple-description coding (MDC), error-resilient video coding, MIMO systems, space-time processing, spatial multiplexing, video mapping, singular value decomposition

I. INTRODUCTION

CONVENTIONAL single-input-single-output (SISO) wireless communication systems have reached their limit in meeting today's ever-growing demands for higher throughput and enhanced quality of service. Although the improvements associated with MIMO (multiple-input-multiple-output) systems at the physical (PHY) layer have been investigated in great detail [1-3], the ways in which these benefits can be used to boost the performance at the application layer remain unclear. This paper will investigate the influence of basic MIMO techniques on the quality of transmitted video.

Two complementary MIMO techniques are explored: space-time block coding (STBC) and spatial multiplexing (SM). STBC focuses on obtaining maximum possible diversity with a simple decoding algorithm, without offering any coding gain [2, 12]. A very desirable feature of STBC is its use of a simple maximum likelihood decoding algorithm based on linear processing at the receiver. In contrast, SM achieves an increase in throughput with no requirements for

additional spectrum [3, 13]. SM relies on transmitting independent data streams from each transmit antenna. These data streams can be multiplexed from the incoming source stream. If N transmit and receive antennas are present then, under certain conditions, data can be sent at N -times the rate of a standard terminal.

The key point under investigation is how to decompose video and map it onto multiple wireless channels, so that the PHY layer improvements obtained from MIMO techniques can further be enhanced. This paper proposes the use of multiple-description coding (MDC), a technique so far used primarily for wireline transmission. Before elaborating on the system model, the fundamental principles behind MDC and the specific method used in the simulations will be explained. Performance of MDC combined with STBC and SM is then evaluated through simulation scenarios based on practical transmission situations.

II. SLICE-GROUP BASED MDC (SG-MDC)

Transmission of highly sensitive video content over error-prone networks, using wireless and/or IP methods, can result in severe packet loss and image impairment. One way of addressing this issue is to use embedded coding, where several sub-streams are generated from the source video [4]. MDC is an example of a non-hierarchical approach to embedded coding, which has been proposed in recent years to increase robustness of video transport over fixed networks. The purpose of MDC is to introduce redundancy at the encoder to combat errors introduced in the channel. MDC schemes exploit path diversity and overcome the drawbacks of layered coding schemes which will result in catastrophic failure when the base layer is lost. The generated descriptions are of the same importance, and each of them can reconstruct video of acceptable quality independently. This can greatly improve the decoded video quality in a multiple channel environment when one of the channels has failed [5, 6].

Traditionally conceived with a view to being deployed in the wireline environment for transmission over two channels, each of which is either error-free or fails completely [6], MDC has evolved and has been adapted to lossy packet networks. The extension of this to the wireless environment using MIMO systems provides significant opportunity for performance gain.

The increased error-robustness of MDC methods comes at the expense of increased redundancy and subsequent lower efficiency when the transmission is error-free or when packet error-rates (PER) are very low. However, impressive gains obtained from MDC with respect to single-description coding (SDC) emerge when the PER is increased—the superiority of MDC becomes undisputed [5, 8]. Work presented in this paper builds on this fact by further adapting MDC to the wireless MIMO environment and exploiting MIMO transceiver techniques.

SG-MDC, based on the Slice Group coding tool of the H.264/AVC standard [7], is used in this paper. A special version of this type of MDC tool, which uses three motion-compensation loops (3-L SG-MDC) [5], has been chosen for its flexibility. This is reflected in its efficient trade-off between central-decoder quality and redundancy levels.

III. PROPOSED SYSTEM MODEL AND SIMULATION SET-UP

Different video-coding techniques, including MDC, combined with space-time coding for MIMO systems have been investigated to a certain extent, most recently in [9]. This paper aims at furthering this work by applying state-of-the-art MDC and looking into both STBC and SM in order to compare and contrast these two complementary MIMO techniques.

A. Combined MDC and MIMO-STBC

A block-diagram of the transmitter for the proposed MIMO-STBC system is shown in Fig. 1. For this study, a WLAN physical layer simulator employing MIMO techniques [1] was utilised to evaluate the WLAN PER performance. The physical layers of 802.11a and 802.11g are based on the use of OFDM. The physical layer provides several modes, each with a different coding and modulation configuration (Mode1: BPSK $\frac{1}{2}$ rate, Mode2: BPSK $\frac{3}{4}$ rate, Mode3: QPSK $\frac{1}{2}$ rate, Mode4: QPSK $\frac{3}{4}$ rate, Mode5: 16QAM $\frac{1}{2}$ rate, Mode6: 16QAM $\frac{3}{4}$ rate, Mode7: 64QAM $\frac{3}{4}$ rate).

The 2×2 STBC system is based on the Alamouti scheme [2, 12]. Despite the fact that there are two transmitting antennas, there is no content mapping flexibility. In this respect the transmitting system behaves like a conventional SISO system, albeit with significantly improved robustness.

However, in the uncorrelated channel model, it is sensible to assume that the channel conditions for two packets sent at two different times should be independent and therefore unlikely to both suffer from bad channel conditions. This enables us to alternate between the packets of the two descriptions on a frame-by-frame basis (depending on the length of possible error bursts and the resultant interleaving depth) and compare the performance of such a system with the one that uses an SDC representation.

In the case of MDC, CIF video sequences used in the simulations throughout the experiment were encoded and transmitted in the following way. Each of the two descriptions consists of 9 packets per frame, containing data for one of the two slice groups from the central encoder, along with the redundant information, in accordance with [5].

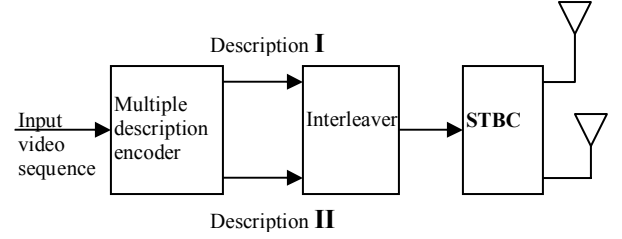


Fig.1. Simplified block-diagram of the proposed MDC/STBC system. The MDC encoder employed is the 3L-SG-MDC one, and the interleaving of the two descriptions is done on a frame basis.

Descriptions can either be sent in alternation on a frame-by-frame basis, or alternatively, depending on the error-pattern characteristics, a deeper interleaving depth could be used. This was not however used in this paper since it introduces additional latency at the decoder. At the packet level, SDC video is, in the case of MIMO-STBC system, transmitted simply as if a SISO system were used.

In order to ensure a fair comparison between MDC and SDC performance in terms of objective video quality (decoded video PSNR vs. SNR) the input video is encoded at the same bit-rate for both MDC and SDC cases. As mentioned earlier, this means that in the absence of errors, SDC outperforms MDC. However, according to the results presented later in this paper, as soon as average packet error loss exceeds 0.5-1%, MDC's benefits become apparent in terms of both objective and subjective quality.

It should be noted that the method employed for corrupting the transmitted video stream has been to discard all corrupted packets. Although other methods based on improved FEC or the use of ARQ performed by higher layers may give better results, this simple technique is very valuable because of its low latency and is applicable in the broadcasting mode, where ARQ is not employed. Notwithstanding, the PHY layer used in the simulations employs powerful channel coding that, coupled with STBC scheme, yields significant improvement over the SISO case in terms of BER. If however bit-errors do slip through the net, the corresponding packet is dropped. Further protection is offered at the application layer, where, by virtue of advanced error concealment tailored to MDC [5], packet loss is further compensated for by taking into account the properties of MDC video.

B. Combined MDC and MIMO-SM

SM consists of splitting the original bit-stream into several sub-streams, ranging from independent to partially redundant to fully redundant [3, 10]. SM is also known as Bell Laboratories Layered Space Time Architecture (BLAST). It represents a direct exploitation of the available space-time resources [13]. This transmission of independent streams of data relies heavily on the independence of fading processes in different spatial channels. When the generated sub-streams are fully independent, SM increases transmission rate proportionally to the number of transmit-receive antenna pairs.

The channel gain matrix is also known as the channel state information (CSI). Many MIMO systems only require knowledge of the CSI at the receiver. However, when prior CSI knowledge is available at the transmitter (full CSI), a range of enhanced MIMO configurations are possible.

An obvious way of demultiplexing the received streams is to multiply the received vector with the inverse of the channel matrix and use the obtained result as an estimate of the transmitted vector. Unfortunately, this suffers from the usual problems associated with finding the inverse of a matrix, and induces the additional problem of noise enhancement. Often linear or even non-linear equalisation techniques are employed as an alternative [11]. Linear processing detection techniques include zero forcing (ZF) and minimum mean squared error equalisation (MMSE). In this study a ZF detection algorithm was used.

Singular value decomposition (SVD) significantly reduces the resulting decoding complexity of SM systems by reducing the system to several decoupled SISO systems, thus avoiding the exhaustive search needed in a maximum likelihood (ML) MIMO receiver [10, 11]. Before presenting the results, SVD will briefly be explained.

Any $M \times N$ matrix H can be decomposed as follows:

$$H = U \cdot \Sigma \cdot V^H \quad (1)$$

where U and V are two unitary matrices of size $M \times M$ and $N \times N$, respectively, and Σ is an $M \times N$ diagonal matrix that contains so-called singular values of matrix H , which are always non-negative. By substituting the SVD decomposition given in (1) into the basic MIMO operation equation $y = H \cdot x + n$, the following is obtained:

$$y = U \Sigma V^H \cdot x + n \quad (2)$$

Left-multiplying (2) by U^H and using the unitary property of matrix U yields

$$\begin{aligned} U^H \cdot y &= U^H U \Sigma V^H \cdot x + U^H \cdot n \\ &= \Sigma V^H \cdot x + U^H \cdot n \end{aligned} \quad (3)$$

If vectors $U^H \cdot y$, $V^H \cdot x$ and $U^H \cdot n$ are denoted \tilde{y} , \tilde{x} and \tilde{n} respectively, (3) simplifies to:

$$\tilde{y} = \Sigma \cdot \tilde{x} + \tilde{n} \quad (4)$$

Since Σ is a diagonal matrix, (4) means that the original channel has been transformed into $\min\{M, N\}$ uncoupled channels. Each of these sub-channels has a gain that corresponds to a single singular value of the channel matrix H . The decoupling is performed by virtue of transmit precoding and receiver reshaping [10, 11]. The gains of these SISO channels are singular values of a single matrix and in that sense are not independent. Nonetheless, the channels do not interfere with each other. This system performance gain is called multiplexing gain. However, some of the sub-channels can exhibit extremely poor performance, depending on the fluctuations in the singular value levels [8, 10]. In addition to this, it should be stressed that SVD can only be performed when the channel matrix is known at both the transmitter and

receiver (full CSI).

In this paper, different mappings of the MDC streams to the SM streams will be analyzed. Performance results will be shown for the cases of full CSI and no CSI at the transmitter. SDC video, in the case of a MIMO-SM system, is transmitted by simple de-multiplexing: video is treated like any other type of digital data—packets are split into odd and even packets (in the case of the 2×2 MIMO system in question), transmitted over the two channels and then reassembled at the receiver.

IV. SIMULATION RESULTS

The effects of the described MIMO-STBC transmission scenario on two CIF sequences, “Paris” and “Mobile”, are shown in Fig. 2 and Fig. 3, respectively. For these results transmission mode 5 (16QAM $\frac{1}{2}$ rate) has been employed. The obtained PSNR values are averaged across the whole sequence and over several different experiments for each SNR. Radio-parameters of the simulated MIMO channel include 20ns rms delay spread in a Rayleigh environment with 90 degrees of angular width (correlated channels scenario). The angular width (uniform distribution) will determine the correlation between the antennas [1]. This is typical for a non-line-of-sight (NLOS) office/home scenario.

The results clearly show a substantial gain in the objective quality of the reconstructed video, which is evident especially within the range of SNR values between 6dB and 11dB. This range roughly corresponds to the PERs of 30% down to 1%, for the given transmission mode and packet length, as depicted in Fig. 5.

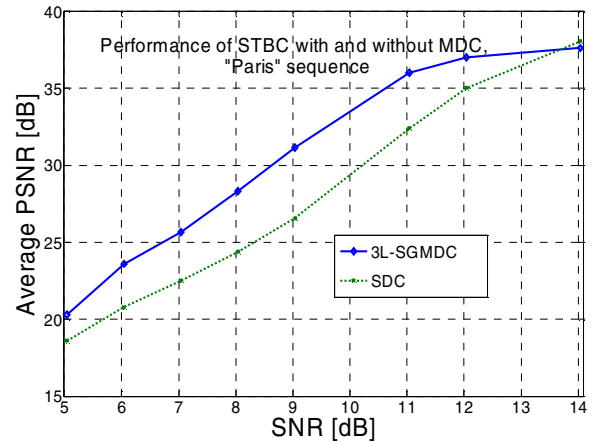


Fig. 2. Simulation results for the first 150 frames of the “Paris” sequence transmitted using Mode 5 of the 802.11 a/g PHY layer model with STBC.

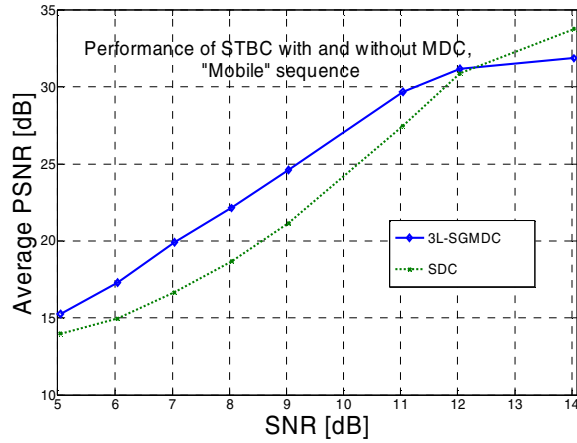


Fig. 3. Simulation results for the first 150 frames of the “Mobile” sequence transmitted using Mode 5 of the 802.11 a/g PHY layer model with STBC.

The proposed technique results in a significant improvement in subjective quality of the encoded sequences, as illustrated in Fig. 4. The two sequences are encoded at the same bit rate, which explains the cross-over point that occurs at low PERs (high SNRs), along with the convergence of the curves in Fig. 2 and Fig. 3 in the region of high PERs. This enables a fair comparison between the two techniques, and shows the superiority of the proposed method for a range of PER values expected in real systems.

Fig. 6 and Fig. 7 show the results for the cases of the “Paris” sequence transmission over MIMO-SM systems without CSI at the transmitter and with full CSI, respectively. In the case of MIMO-SM without CSI at the transmitter, zero-forcing (ZF) is used to reconstruct the original streams. As for the communications part, the same transmission scenario is used as in the case of MIMO-STBC detailed earlier.

As can be seen from Fig. 6, when MIMO-SM (ZF) is used, no benefit is obtained from deploying MDC. The standard way of demultiplexing packets at the transmitter and then reassembling them at the receiver outperforms MDC. This is due to the fact that MIMO-SM (ZF) produces highly correlated error-patterns i.e. it is highly probable that both of the descriptions will be either lost or received.

However, in the case of MIMO-SM (SVD), significant improvements are obtained from decomposing video in an intelligent way by using MDC, as shown in Fig. 7. The two resulting sub-channels are independent and produce uncorrelated error-patterns, ensuring that at least one of the two descriptions is received. This architecture is thus preferable in terms of optimising the potential for video transport over MIMO systems [8].

V. CONCLUSIONS

This paper has presented a new approach to the efficient and robust transmission of video over wireless channels, through a combination of MIMO and MDC technology. With correct design, MDC can exploit the interactions between

descriptions when losses occur in multiple-channel wireless communications to reliably recover the video. Results indicate improvements in average PSNR of decoded test-sequences of up to 8dB in the case of MIMO-SM (SVD) and up to 5dB in the case of MIMO-STBC, compared to standard video transmission. This is also supported by significant subjective quality enhancements. These results provide a framework for future wireless video transport and underscore the need for channel-aware video-encoding, if benefits gained from deploying MIMO architecture are to be fully realised.

VI. ACKNOWLEDGEMENTS

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Fig. 4. A frame from the reconstructed video sequence “Paris” transmitted using STBC in conjunction with MDC is shown at the top. The corresponding frame from the SDC sequence is shown below, in order to demonstrate the effects of the proposed system on the subjective quality of transmitted video. The average PER for this case is approximately 6%.

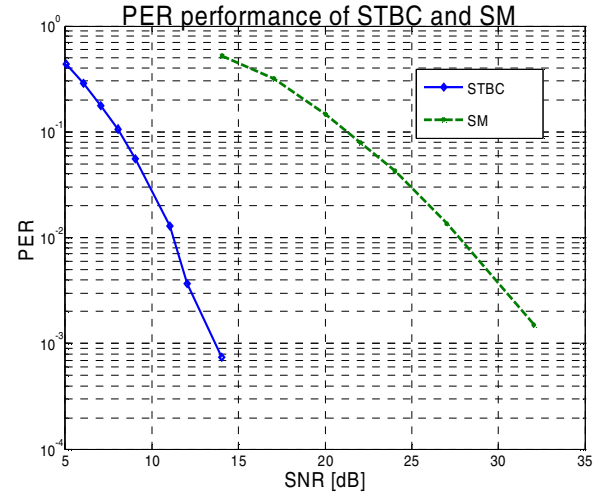


Fig. 5. PER performance of STBC and SM (ZF) Mode 5 for the described channel scenario.

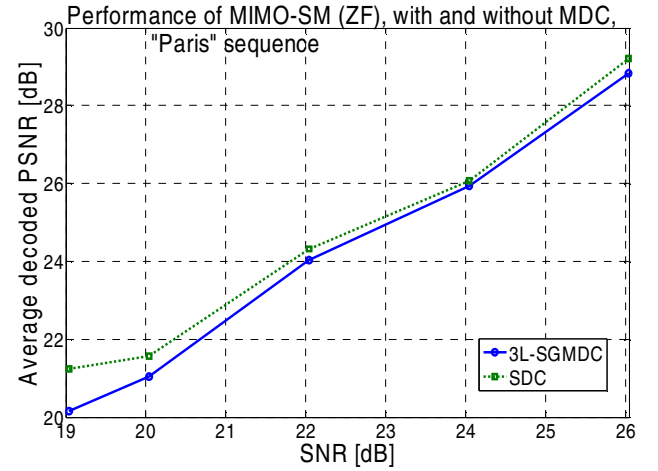


Fig.6. Simulation results for the first 300 frames of the “Paris” sequence transmitted using Mode 5 of the 802.11 a/g PHY layer model with SM-ZF.

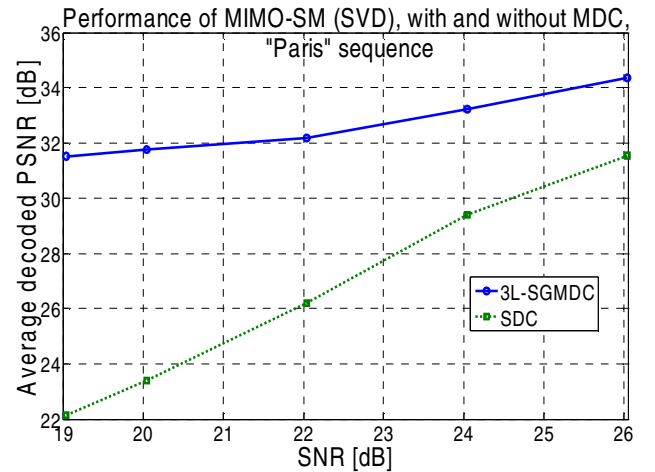


Fig.7. Simulation results for the first 300 frames of the “Paris” sequence transmitted using Mode 5 of the 802.11 a/g PHY layer model with SM-SVD.